Observations of Exozodiacal Dust with the Keck Interferometer Nuller

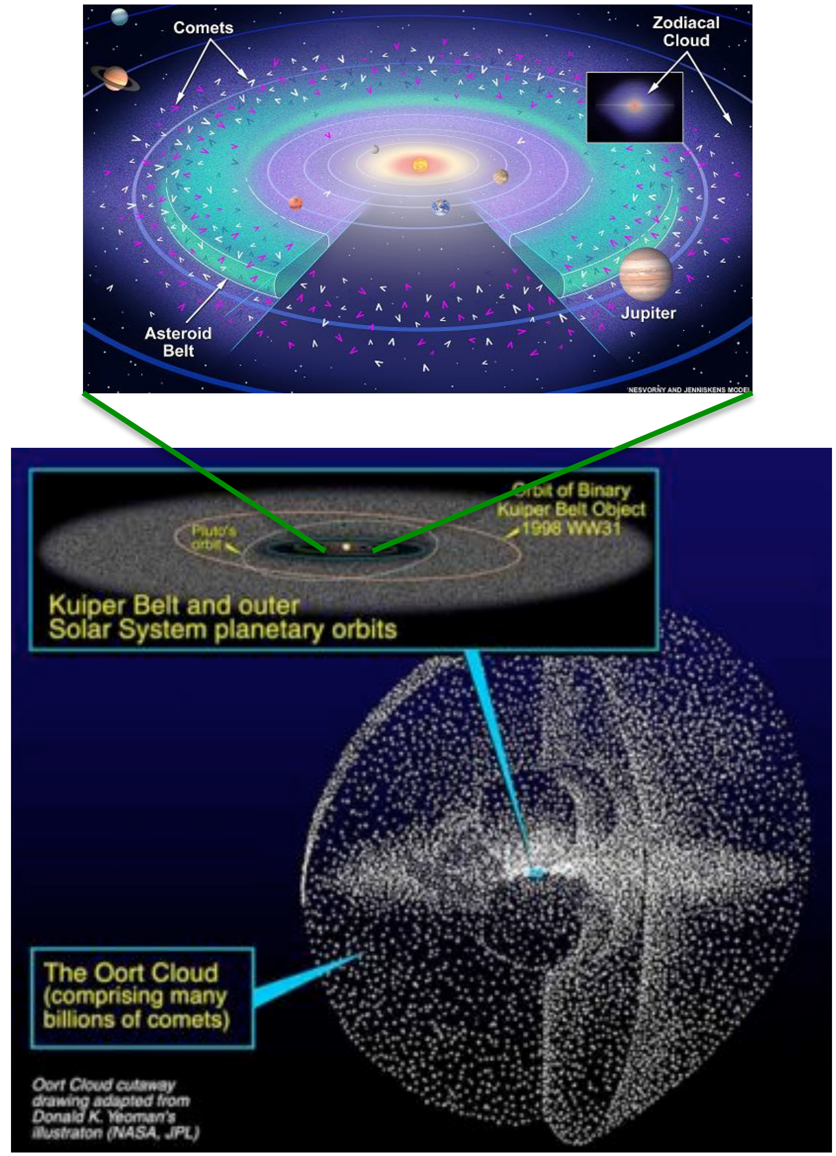
Rafael Millan-Gabet
Caltech/NExScI

G. Serabyn (JPL)
B. Mennesson (JPL)
W. Traub (JPL)
K. Stapefeldt (JPL)
G. Bryden (JPL)
R. Barry (GSFC)
B. Danchi (GSFC)
M. Kuchner (GSFC)
S. Ragland (WMKO)
M. Colavita (JPL)
JPL Team
NExScI Team
WMKO Team

JPL Center for Exoplanet Science Colloquium
July 22 2010

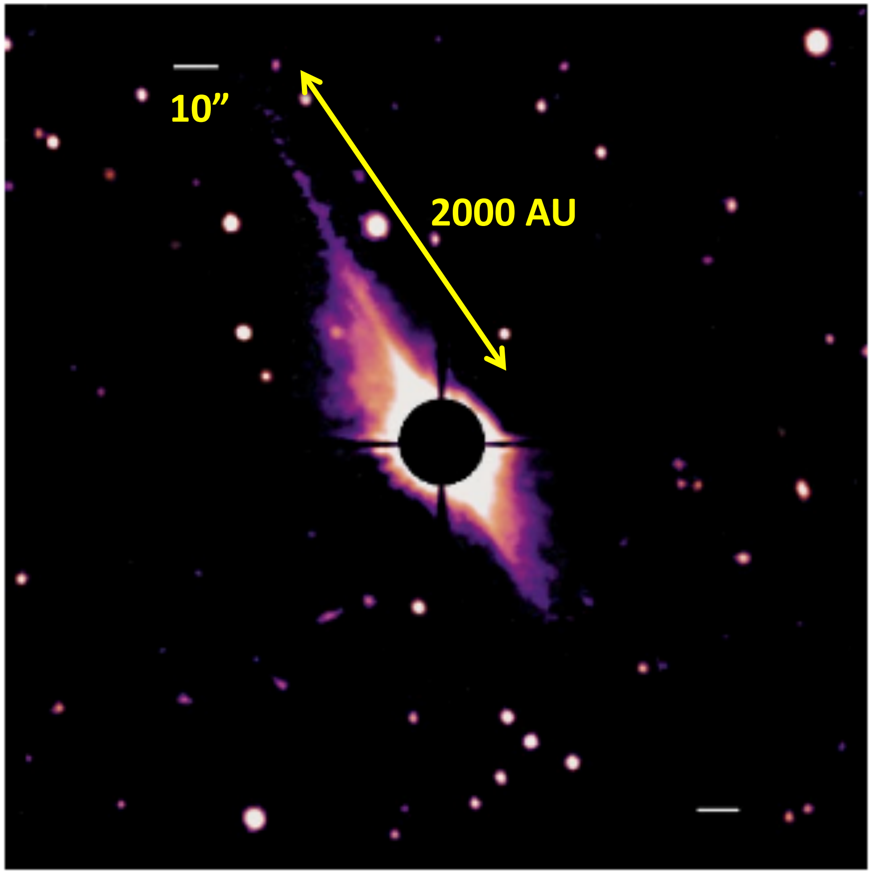
The example of our Solar System

- **Debris disk:**
  - **Dust generated by collisions between larger bodies in asteroid and Kuiper belts and by comet outgassing.**
- **Zodiacal cloud:**
  - **200-500K dust out to ~5AU, associated with the asteroid belt.**
  - **f = Ldust/Lsun ~ 10^-7 (measured).**
  - **10^-10 of mass in planets, but x100 IR their luminosity.**
- **Kuiper belt:**
  - **<30-200K dust at 30-50AU.**
  - **Volatile cometary material.**
  - **f ~ 10^-6 (inferred).**
  - **1/10-1/100 Mearth.**
- **Dust survival times are short (100-1000 Myr) ➔ any dust found in stars older than few 10sMyr must be recently formed & continously generated.**



Circumstellar dust around other mature stars

- Discovered by IRAS (1983).
- Observationally characterized since then by a variety of instruments (ISO, ground based IR and sub-mm imaging, Spitzer, NIR interferometry).
- Main techniques:
  - Measure photometric excess within some IR band.
  - Imaging. Reveals spatial structure.
- Our current levels of zodi and Kuiper belt dust are undetectable around other stars.
- Note: exo-Kuiper belts were discovered before our own…



Bet Pic (UH 2.2 m, Kalas 2000)

Why study debris disks?

- Time scales for debris disk evolution may help understand terrestrial planet formation (see e.g. Wyatt 2008).
- Use disk structure to infer the presence of unseen planets (e.g. Wolf 2007).
- Knowledge of exozodi levels and structure is needed in order to properly design future terrestrial planet finding/imaging missions (see e.g. Exoplanet Community Report 2009, Exoplanet Task Force report, Lunine 2008):
  - True for both vis coronographs and IR interferometer concepts.
  - Knowledge of the exozodi levels for all candidate stars would allow a greatly optimized instrument and strategy design.
  - Exozodi photons impact the needed integration times, or sample sizes for given mission duration.
  - Another problem: distinguish planets from disk blobs.

Some general things we have learned: Ubiquity

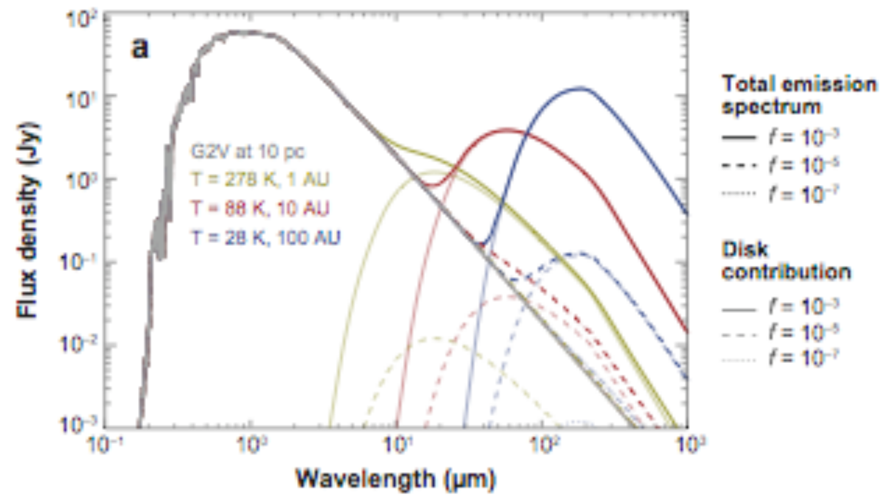
- A ubiquitous phenomenon! Many 100s detected. (e.g 30% of A stars. Detection rates vary by stellar type, age, measurement band …)

- Example, for old solar-type stars:
  - 13% have 70um excess (Bryden 2006, Beichman 2006, Spitzer/MIPS).
  - Warm dust (<30um) is rare (e.g. 2/41 Beichman 2006b or 1% Lawler 2009, 8-13um Spitzer/IRS).
  - (consistent with evolution models given the stellar ages and detection thresholds).

Levels

- Due to instrument limitations, known systems have dust excess x100-1000 higher than in our Solar system.
- Examples (Beichman 2006, Lawler 2009):
  - Spitzer/MIPS 70um: sensitive to excess 20-30% above star.
  - Spitzer/MIPS 24um: sensitive to excess 10% above star.
  - Spitzer/IRS 8-13um: sensitive to excess 1-3% above star. That is σ(Fdust/Fstar) = 0.01-0.03.
  - E.g. if all the excess came from dust at the thermal equilibrium radius for Tdust=367K (blackbody peak at 10um), these translate into Ldust/Lstar < 1.0-1.5x10^-4, which is x1000-1500 the nominal Solar value.

Wyatt 2008

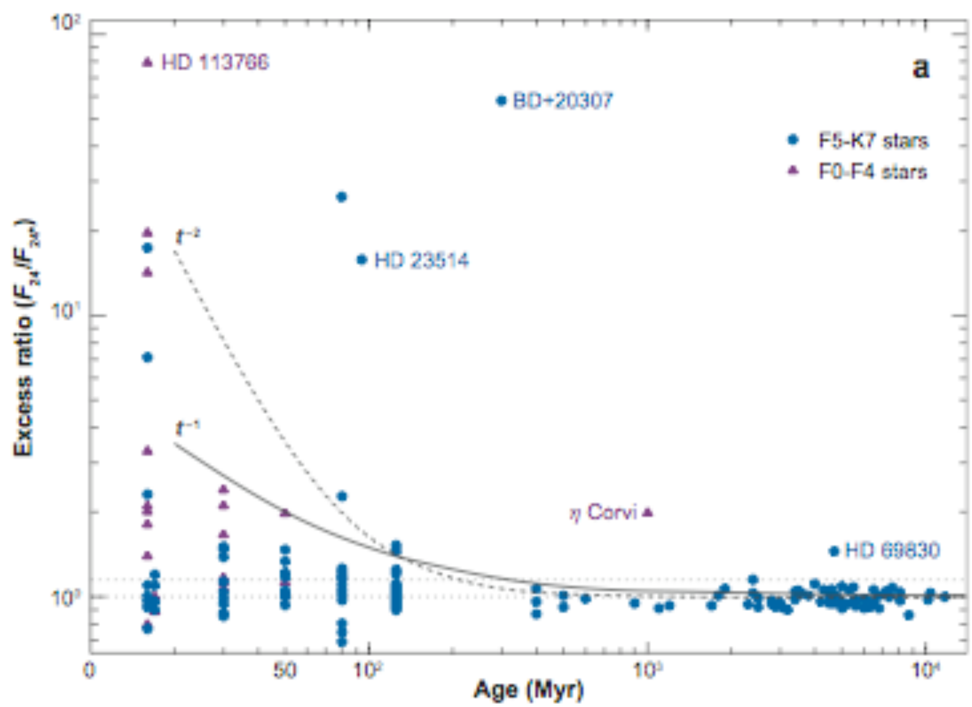


Difficulties:
• absolute calibration.
• predicting stellar flux from shorter wavelength measurements.

Evolution

- In general: older stars have less excess emission.
- A-stars: 150Myr/t upper envelope time-scale.
- FGK stars:
  - 24um: evolve x10 faster.
  - 74um: slow decrease, persists for a longer time than 24um, and up to 10Gyr.

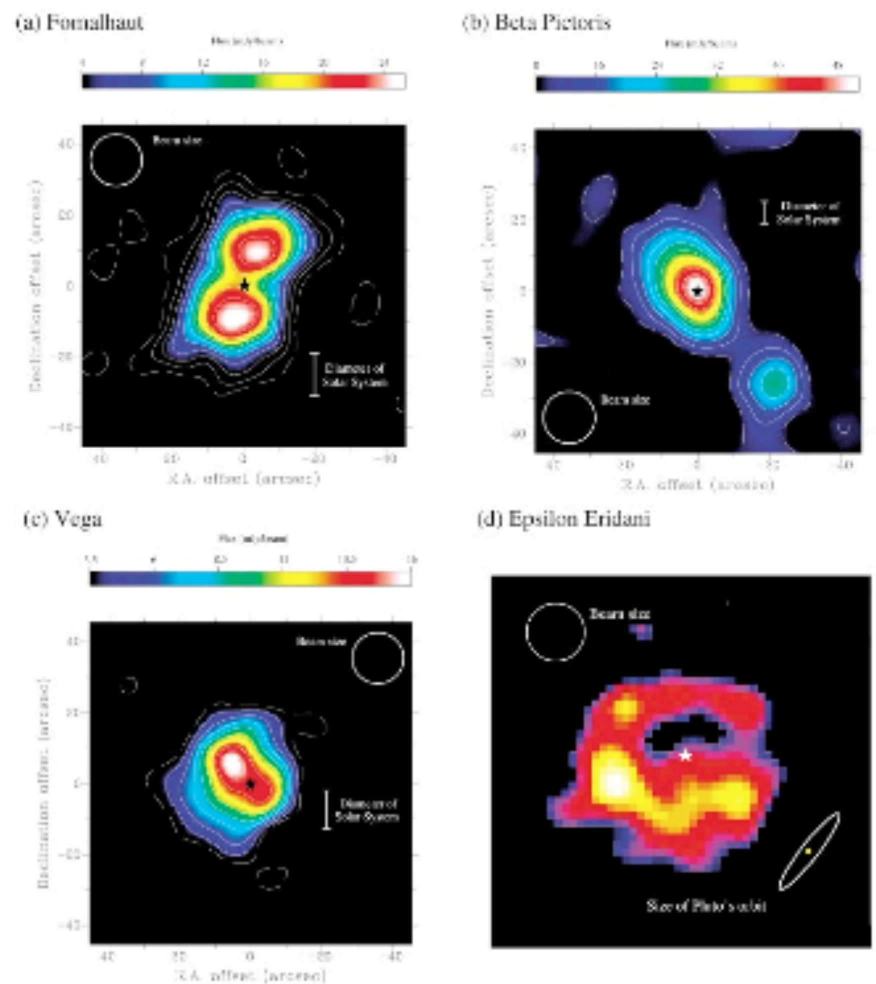
Wyatt 2008



- Theory:
  - Steady state collisions evolution explains many of the general features.
  - But stochastic evolution also required (large spread at any age).
  - Transient hot dust from collisions, or derived from an outer planetesimal belt (where dust has longer lifetimes).

Morphology

- Only a few systems have been imaged.
- Rich collection, even in this small sample, of features: warps, offset symmetry centers, clumps, spirals, asymmetries (as predicted if planets are also present…)
- Challenges any particular interpretation of spatially unresolved data critically dependent on a particular geometry assumption (e.g. Vega & Fomalhaut have similar SED …).
- Not a good idea to extrapolate inner hot dust levels from outer cold dust measurements…



Zuckerman 2001

The Keck Interferometer

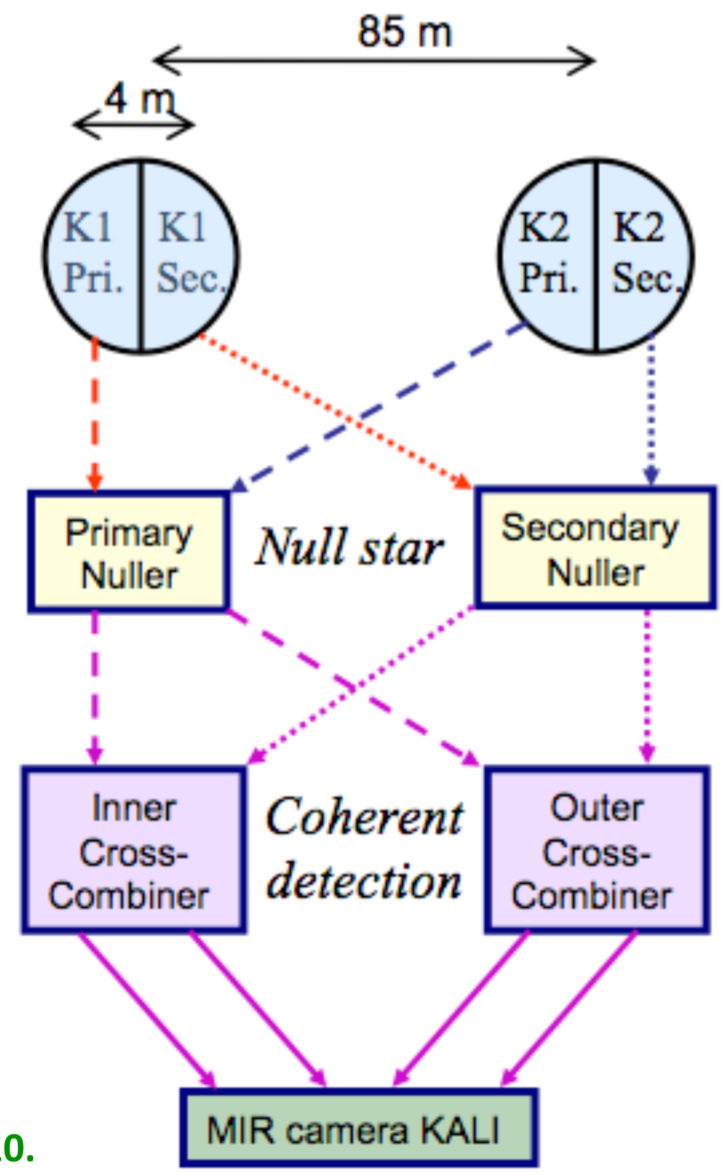
- The 2 Kecks (D=10m) combined as an IR interferometer, Baseline=85m.
- NASA funded. JPL/WMKO/NExScI development & operations.
- Standard Michelson interferometry at H(1.2um), K(2.1um), L(3.5um) bands. R up to 2000.
- Nulling in Nband (8-13 um).
- Development of Dual Field and Astrometric capabilities (ASTRA, NSF funded).

For all the details see: http://nexsci.caltech.edu/missions/KI/

The Keck Interferometer Nuller

- Split each Keck aperture into left and right halves.
- Null the star on the 85m baseline.
  - Accommodates the large dynamic range between the star and surrounding dust.
- Demodulate the output of the long baseline nullers with a second interferometer on a short 4m baseline.
  - Allows detection in the presence of the large thermal background.
  - Also, provides accurate flux normalization.
- The measurement, in essence:

$$"Leak" = L = \frac{XC\ amp\ @\ null}{XC\ amp\ @\ peak}$$

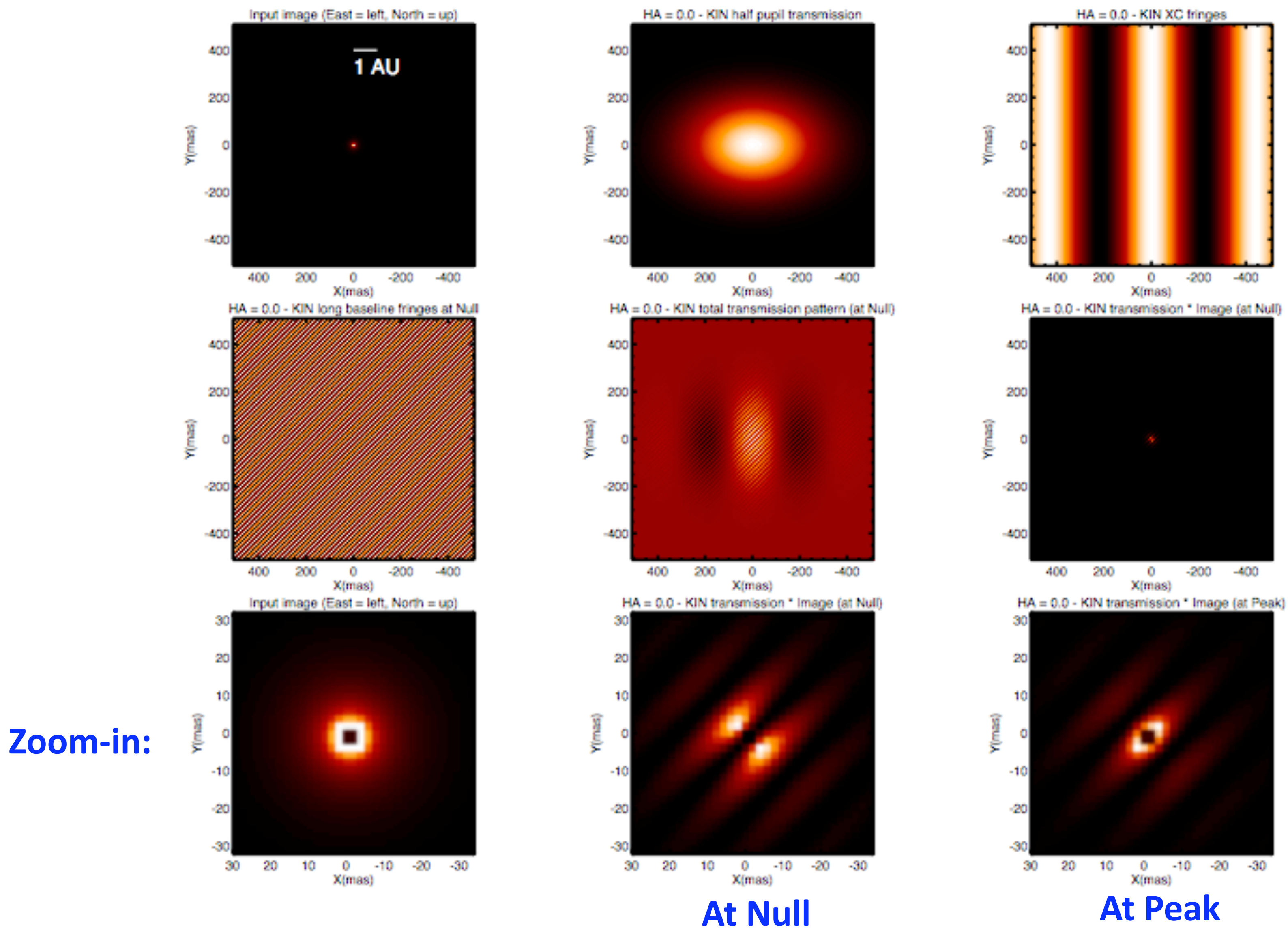


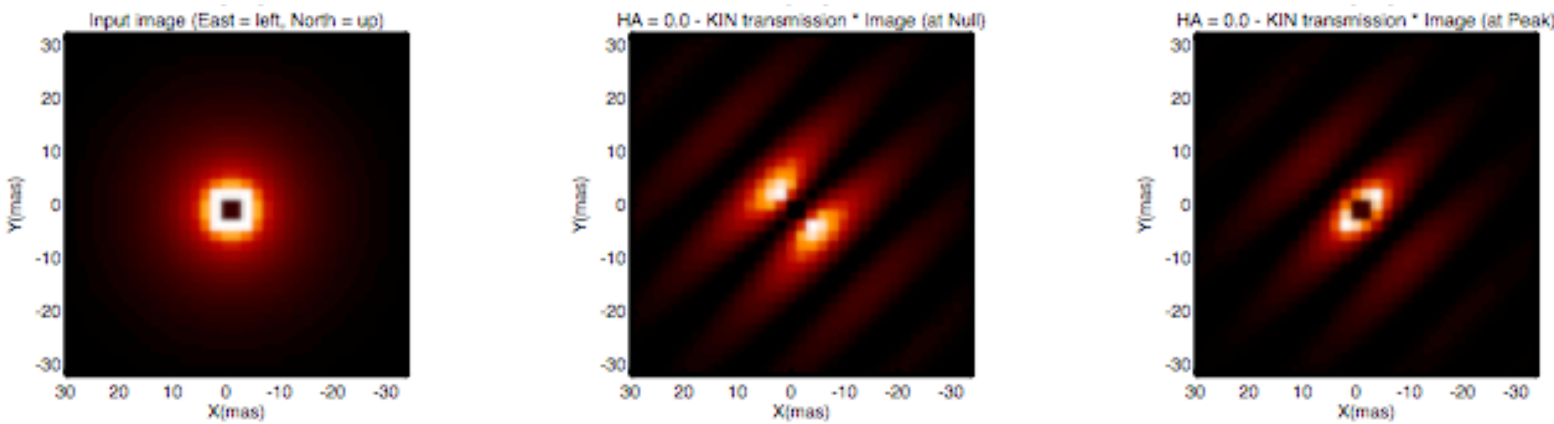
Colavita 2009, 2010.

Key aspects

- **Spectral band:**
  - **8 – 13 um**
  - **10 spectral bins**
  - **λeff = 8.5 um**
- **Long baseline fringes provide sensitivity to inner dust:**
  - **At null, next fringe peak is at $\lambda/(2B)$ = 10 mas.**
  - **Or 0.1 AU at d=10 pc (sample median).**
  - **Compare with e.g.:**
    - **at 8.5 um, blackbody peak is for Tdust = 432K.**
    - **in equilibrium with Lsun at 0.4 AU.**
- **Background limited, therefore:**
  - **The stability of the null is important (not its absolute value).**
- **The Nuller architecture results in better control of systematics and higher calibration accuracy than standard IR interferometry.**
- **Example:**
  - **For single baseline: L = (1 – V)/(1 + V).**
  - **L = 0.01 corresponds to Visibility = 0.98.**
  - **σ(L) = 0.003 (KIN typical) corresponds to σ(V) = 0.006 (0.6%, much better than standard MIR interferometry! (e.g. VLTI/MIDI).**

Sky response





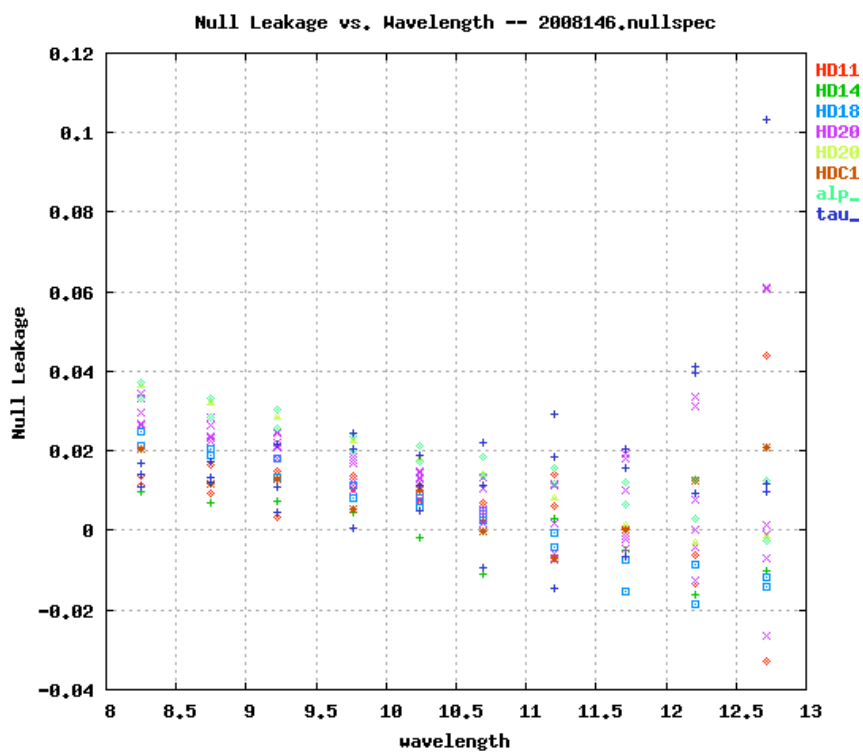
$$(measured\ Leak - stellar\ Leak) = \frac{\iint Brightness * (KINPattern)null}{\iint Brightness * (KINPattern)peak}$$

From a LD model calculation

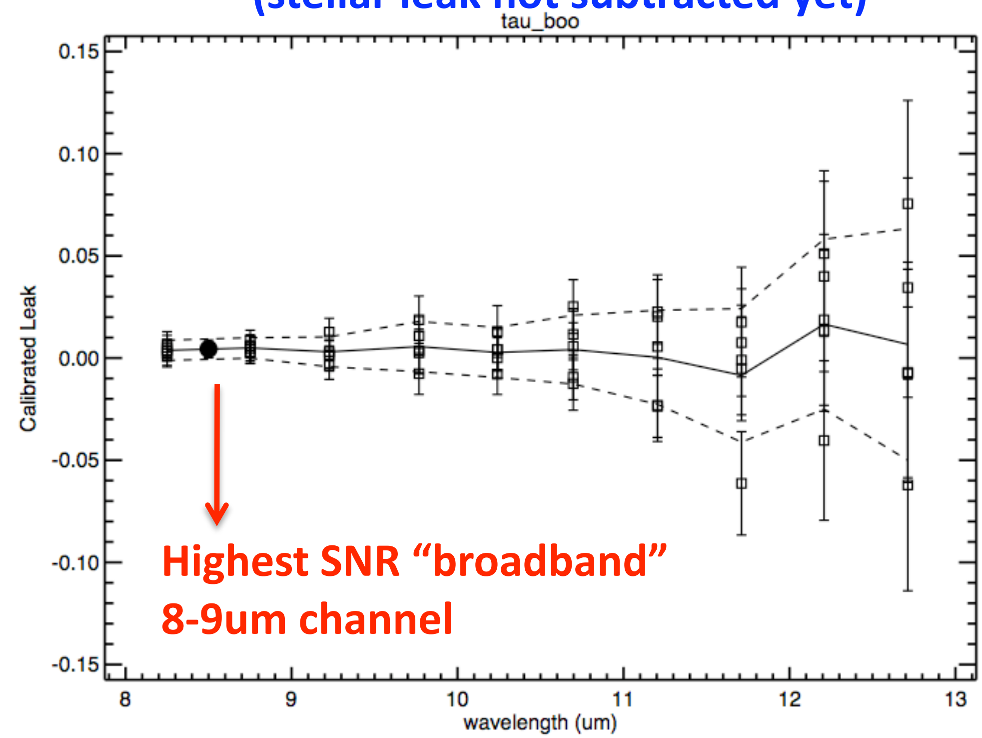
Brightness distribution of zodi cloud only

Example data

Raw



Calibrated
(stellar leak not subtracted yet)



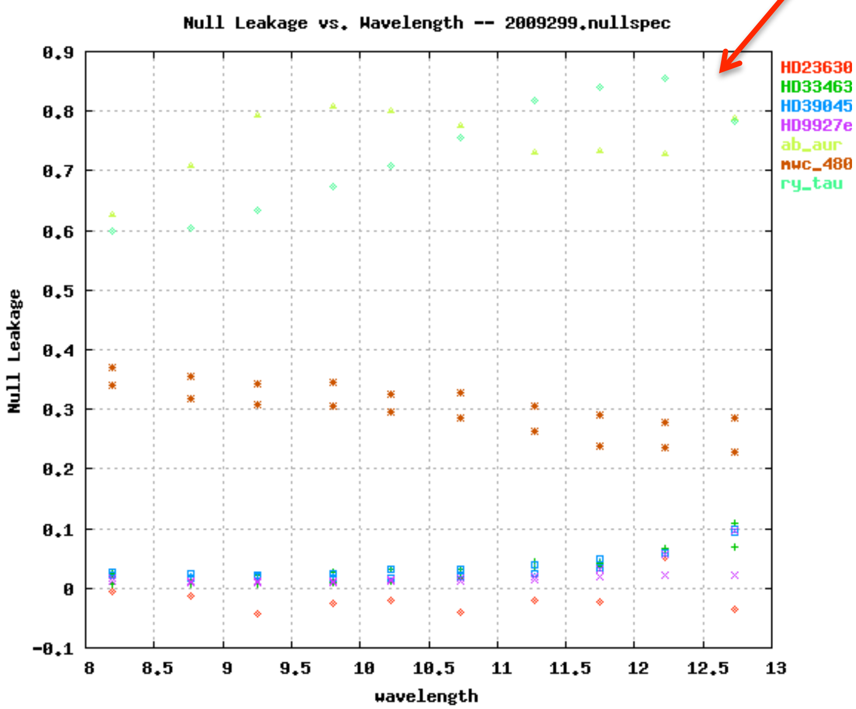
- Responsivity strongly peaked toward the blue.
- Here we use only the most sensitive 8-9um channel.
- Systematic errors also worse for red end of bandpass.
- For the brighter stars the full spectrum can be used.

We can get a large signal too …

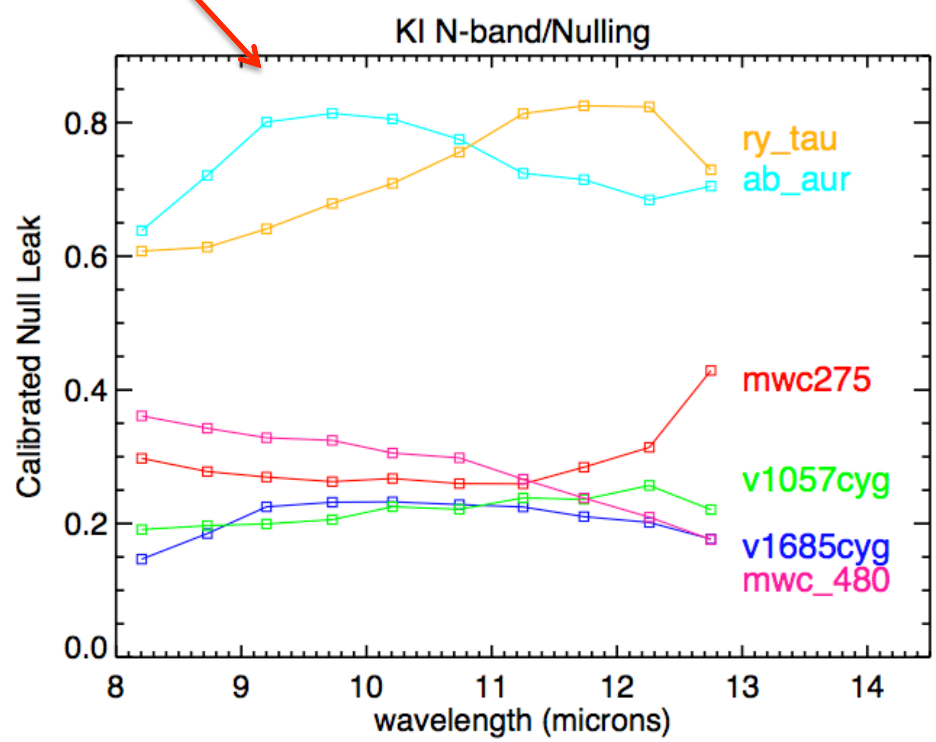
Proto-planetary disk examples

Huge signatures
from disks!

Raw



Calibrated



Performance

- Limiting magnitude: ~ 1.5 Jy at N-band.
- Efficiency: ~ 3.5 hrs for 2 bracketed observations, including all needed setup, and the 5 telescope slews and star acquisitions.
- Formal errors per observation:
  - from scatter among 1000s independent measurements (12 mins of data, 400 msec micro-sequence).
  - σ(L) formal = 0.001 – 0.004 (for this sample).
- External error:
  - from fluctuations among average leak for multiple clusters over different nights.
  - Flux and wavelength dependent.
  - For WB channel and our fluxes, σ(L) ext = 0.002 – 0.0035.
- Typical final accuracy: σ(L) = 0.003 (0.3%).

Colavita, PASP, 2009 or SPIE 2010

The Key Science projects

- Intensive 1-year program.
- 32 nights.
- Feb 2008 – Jan 2009.
- 3 teams selected in response to NASA call:
  - P. Hinz (U of A).
  - M. Kuchner (GSFC).
  - G. Serabyn (JPL).
- 44 targets observed of submitted.
- Nearby MS stars potential targets for future planet-finding missions, or which are known to have debris disks.

The Serabyn sample

Name	Spec Typ	D (pc)	L (Lsun)	Comments
eta Cvr	F2V	18.2	4.7	High dust
107 Psc	K1V	7.5	0.4	binary
1 Ori	F6V	8.0	2.6	
47 UMa	G1V	14.1	1.5	3 RV planets
61 Cyg A	K5V	3.5	0.2	binary
70 Oph	K0V	5.1	0.6	binary
HIP54035	M2V	2.5	0.02	
alp Aql	A7V	5.1	9.8	
bet Com	G0V	9.1	1.3	
bet Vir	F9V	10.9	3.4	
chi1 Ori	G0V	8.7	1.0	
del Tri	G0V	10.8	1.1	
gam Lep	F6V	9.0	2.3	

Name	SpecTyp	D (pc)	L (Lsun)	Comments
gam Oph	A0V	29.0	21.9	
gam Ser	F6IV	11.1	2.7	
iot Peg	F5V	11.8	3.3	binary
iot Per	G0V	10.5	2.2	
iot Psc	F7V	13.8	3.3	
kap1 Cet	G5V	9.2	0.8	
kx Lib	K4V	5.9	0.3	binary
lam Aur	G1IV	12.7	1.7	
NSV4765	K5V	4.9	0.1	
tau Boo	F6IV	15.6	3.0	1 RV planet
the Per	F7V	11.2	2.2	
ups And	F8V	13.5	3.3	3 RV planets

- **Observed 25 systems of 29 allocated.**
- **N-band fluxes: 1.3 – 4 Jy (except Altair 31 Jy).**
- **Means: 3Lsun, d=10.5 pc, 3.7 Jy.**

From calibrated leak to number of zodis

$$(measured\ Leak - stellar\ Leak) = \frac{\iint Brightness * (KINPattern)null}{\iint Brightness * (KINPattern)peak}$$

- Compute and subtract stellar leak from the data (adds small additional error).
- Generate an image of an analog of the solar system zodi around each target, using ZODIPIC (Kuchner, GSFC), for a given disk inclination and PA (recall: exozodi only, no central star, avoid having to sample the stellar disk).
- Compute the 1-zodi expected leak.
- Scale the number of zodis until the predicted leak matches the net measured leak.
- This must be done for *each* ***individual*** *observation*, because the conversion to nzodis depends on the KIN pattern (spatial frequency & orientation), which depends on HA.
- Average observations and clusters in "nzodi space", propagating formal and external errors.
- Repeat for range of dust disk orientations {inc,PA}. The resulting variability is additional error source (small).

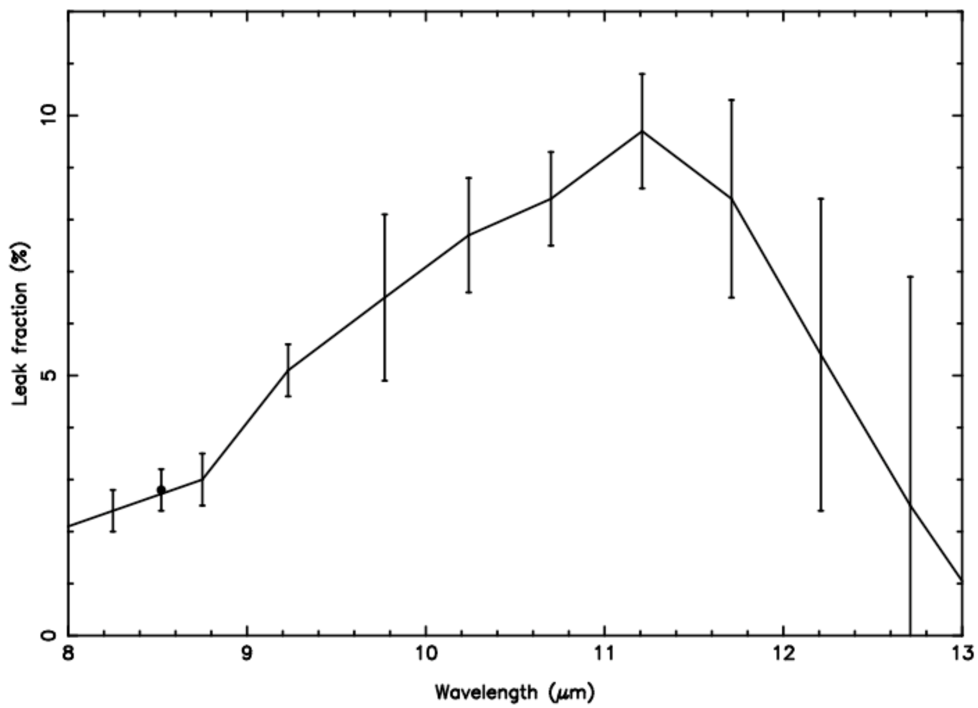
Results

Name	Number Zodis	Nz/error	(3σ) Limit
eta Cvr	1389 +- 273	5.1	…
107 Psc	107 +- 191	0.5	680
1 Ori	43 +- 48	0.9	187
47 UMa	-68 +- 250	0.3	750
61 Cyg A	92 +- 184	0.5	644
70 Oph	67 +- 159	0.4	544
HIP54035	-225 +- 174	1.3	522
alp Aql	564 +- 259	2.2	…
bet Com	236 +- 242	1.0	962
bet Vir	-10 +- 213	0.05	639
chi1 Ori	-60 +- 123	0.5	384
del Tri	-230 +- 178	1.3	534
gam Lep	-81 +- 85	0.9	255

Name	Number Zodis	Nz/error	(3σ) Limit
gam Oph	198 +- 74	2.7	…
gam Ser	-171 +- 87	1.9	261
iot Peg	419 +- 119	3.5	…
iot Per	-281 +- 135	2.1	405
iot Psc	-85 +- 106	0.8	318
kap1 Cet	-115 +- 172	0.7	516
kx Lib	464 +- 326	1.4	1442
lam Aur	76 +- 145	0.5	511
NSV4765	-560 +- 245	2.2	744
tau Boo	150 +- 100	1.5	450
the Per	-54 +- 111	0.5	333
ups And	-72 +- 166	0.4	498

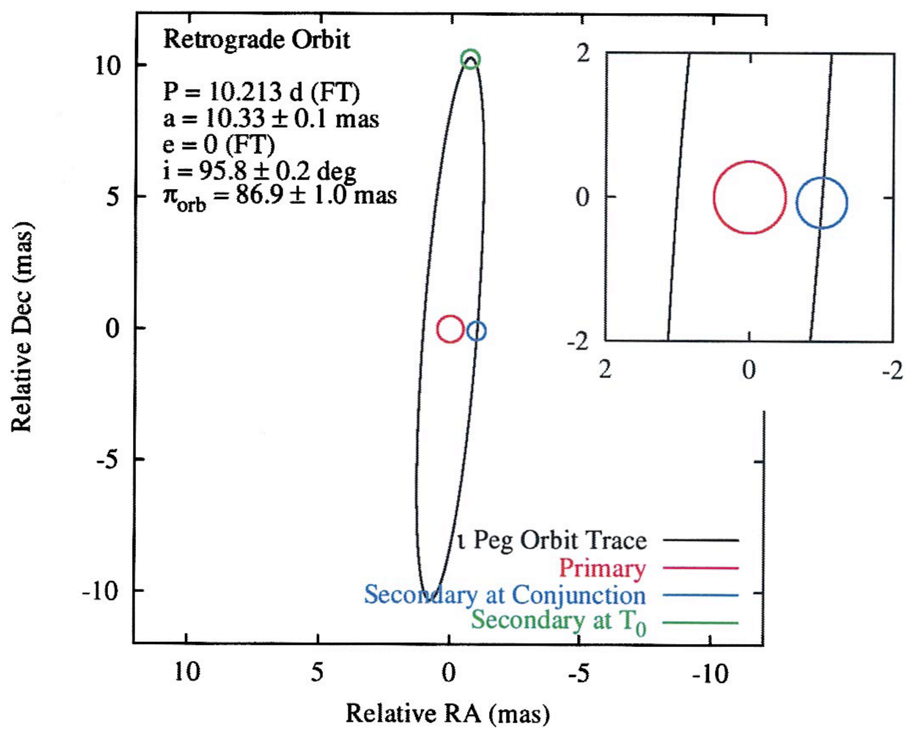
eta Crv

- Nz = 1389 +- 273 (5.1 σ)
- Known to have Spitzer excess at longer wavelengths.
- Spatially resolved at 70um (Spitzer) and 350um (CSO).
- KIN SNR is high enough to make use of the full spectrum.
- Is the dust seen by Spitzer enough to explain the KIN excess leak?
- Will be the object of follow-up analysis.



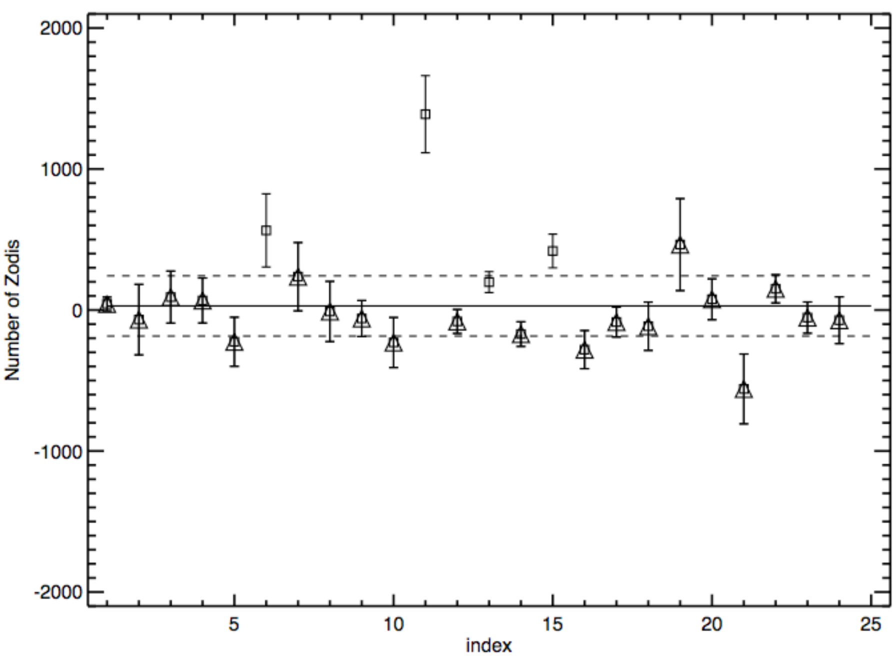
iota Peg

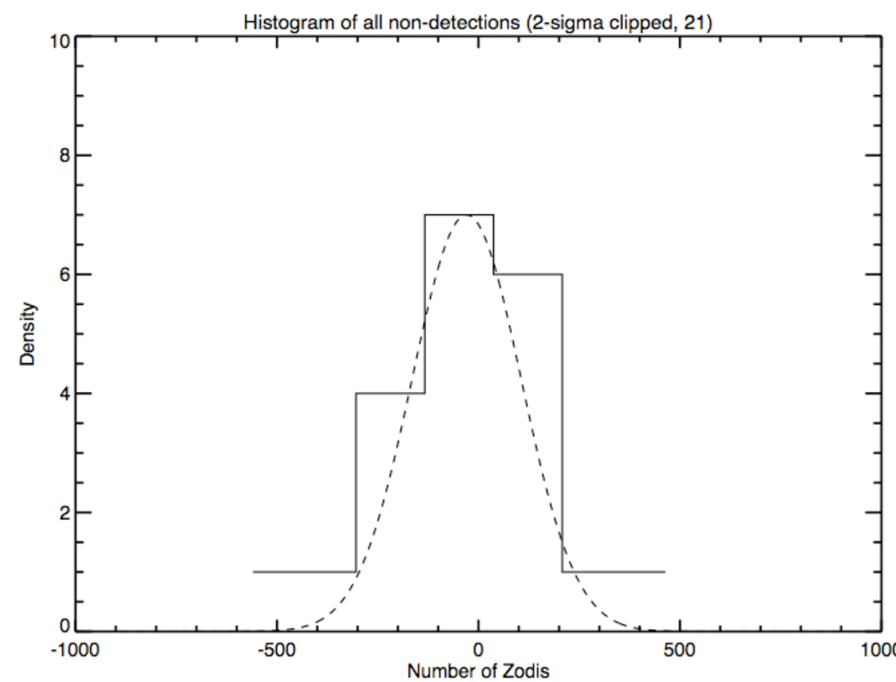
- Nz = 419 +- 119 (3.5 σ).
- Not previously known to have dust.
- Spectroscopic binary with very elliptical apparent orbit (Boden1999).
- Separation in the range: 1 – 10 mas.
- In principle our excess leak is not due to companion (it was too close at the KIN epoch); but we need to double-check.



Non detections

- 21 non-detections (2-sigma clipped).
- weighted mean = -29 zodis
- rms = 135 zodis
- Population: error in the mean = 29 zodis (chi2 = 1.3)





Discussion: Comparison with Spitzer/IRS

- Different modelling aproaches, can the results in terms of nzodis be compared? ➔ put Spitzer/IRS & KIN results on equal footing.
- Spitzer/IRS measures: Fdust/Fstar.
- KIN measures L ~ f * Fdust/Fstar; f is the fraction of light allowed to pass through the instantaneous fringe pattern at null.
- f tends to be ~ 0.4.
- One can derive from the KIN Leak an equivalent Spitzer/IRS measurement:
  – Fdust/Fstar = L/f ~ 2.5 * L
  – Error in this quantity: σ(Fdust/Fstar) = f * σ(L) ~ 2.5 * σ(L).
  – Typical σ(L) = 0.003 ➔ σ(Fdust/Fstar) = 0.0075.
  – Compare with Spitzer/IRS errors (0.01 best case).
  – Not a HUGE difference. Expected improvement factor depends on precise errors in each case (range ~ 30% to x2).
- Do it exactly for the 8 stars in common between KIN & IRS surveys …

Name	IRS (Lawler 2009)				KIN			
	Fdust/F*	3σ max Fdust/F*	3σ max Ldust/L* X10^-5	3σ max Nzodis	Fdust/F*	3σ max Fdust/F*	3σ max Ldust/L* X10^-5	3 σmax Nzodis
47 Uma	-0.02+-0.012	0.036	11	**1000**	-0.003+-0.015	0.044	13	**1337**
bet Com	0.014+-0.010	0.044	8	**800**	0.013+-0.009	0.039	11	**1089**
gam Lep	0.001+-0.01	0.031	8	**800**	-0.004+-0.008	0.024	6	**599**
iot Psc	-0.007+-0.014	0.042	10	**1000**	-0.0003+-0.009	0.027	7	**675**
kx Lib	0.002+-0.010	0.032	16	**1600**	0.010+-0.008	0.035	19	**1951**
tau Boo	0.011+-0.014	0.052	10	**1000**	0.008+-0.008	0.032	8	**773**
the Per	0.003+-0.01	0.033	8	**800**	0.006+-0.008	0.032	8	**802**
ups And	-0.003+-0.010	0.030	10	**1000**	-0.004+-0.008	0.023	6	**613**

$$Ldust/L^* = 3.5x10^{-3} \times \left(\frac{T^*}{5600K}\right) \times \frac{Fdust}{F^*}$$

Here 1-zodi is Ldust/L* = 10^-7

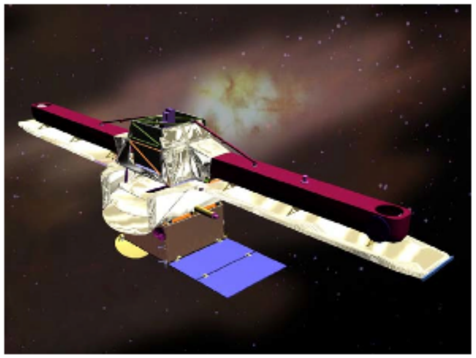
- The different modelling approaches do in fact give similar results.
- KIN/Spitzer-IRS limits not hugely different. On a star by star basis, which provides tighter limits just depends on the errors in the basic measurement.
- **Note**: IRS errors do not include a possible systematic in the stellar flux, to which KIN is immune.

Conclusions

- An important new technique – MIR nulling interferometery -- has been demonstrated.
- In spite of being on the ground and of the thermal background, provides comparable, or somewhat better, performance than space observatory.
- eta Crv: known to have $\lambda > 20$um dust, is here detected at 8.5um. Also shows Si spectrum.
- iot Peg: possible new detection (need to confirm it is not the companion).
- 21 non-detections:
  - average = -29 zodis (i.e. centered around 0).
  - σ = 135 zodis.
  - Error in the mean = 29 zodis. Representative of a uniform population?
  - Average 3σ upper limit = 550 zodis.

What next?

- Need to push down further in knowledge of zodi levels around nearby MS stars:
  - LBTI: 80 stars down to 10 zodis.
  - Do we need to know about 1-zodi levels?
  - A dedicated space mission?



- Still need to solve the problem of dealing with disk inhomogeneities.
  - Characterization of morphologies, or address with appropriate observing strategy?